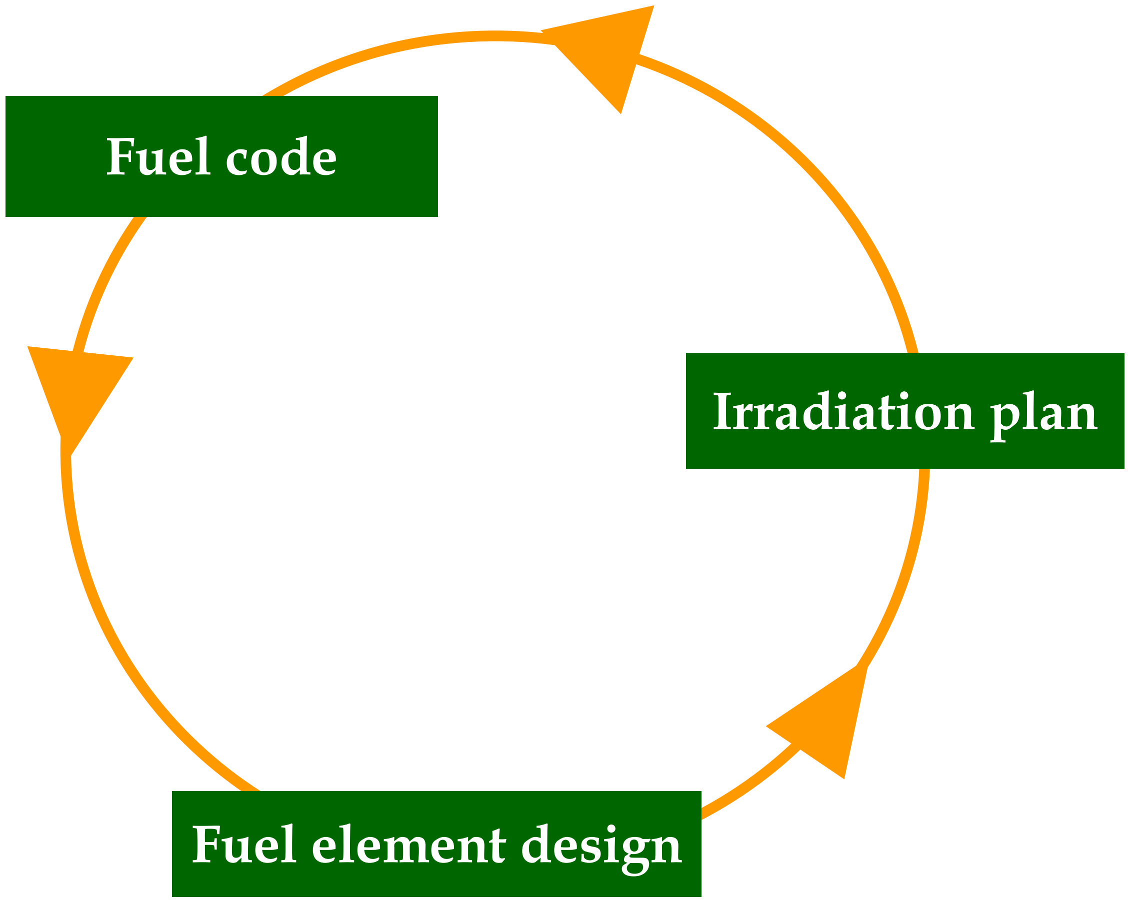
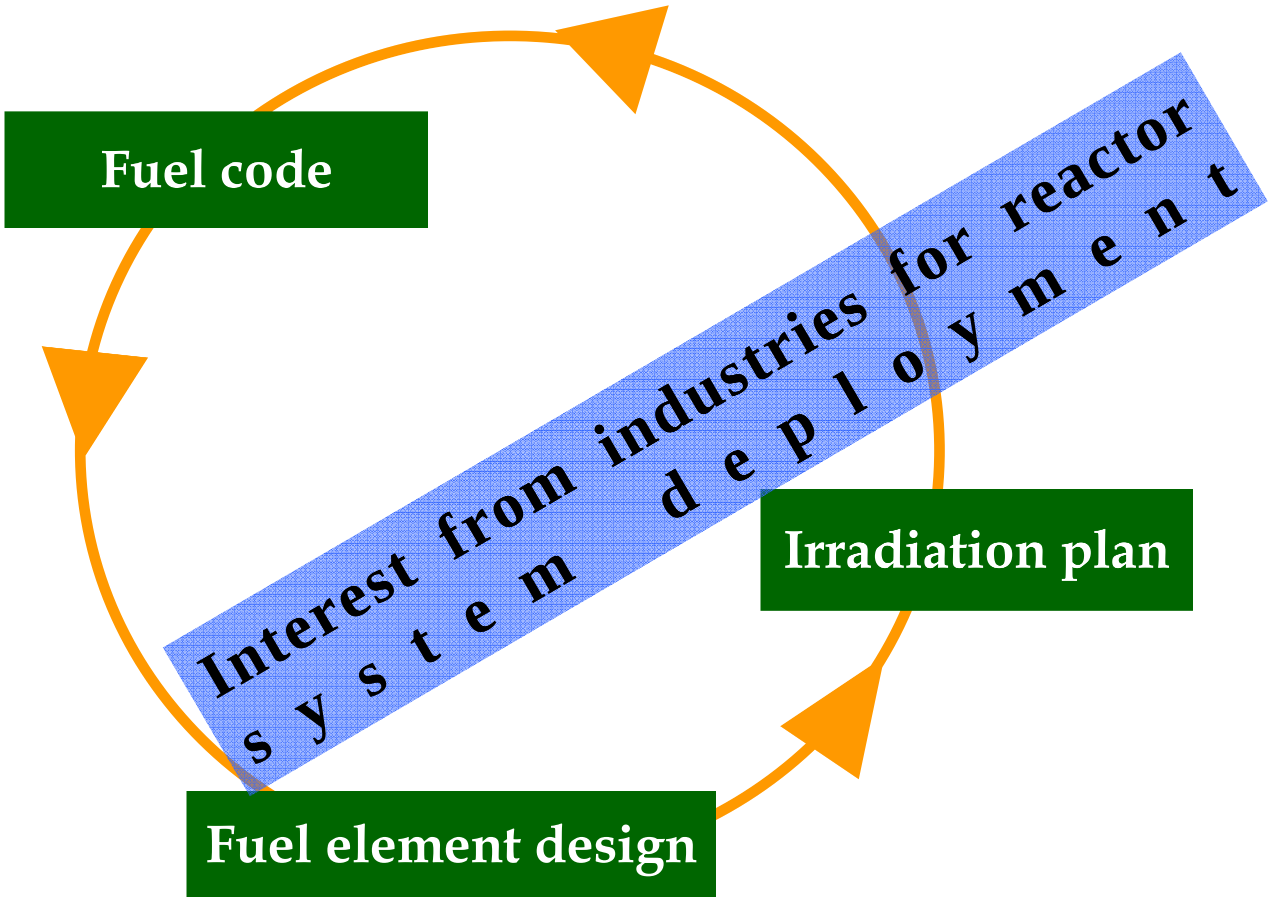
Fuel design, irradiation programme and modelling,

Application to several fuels for GENIV systems.

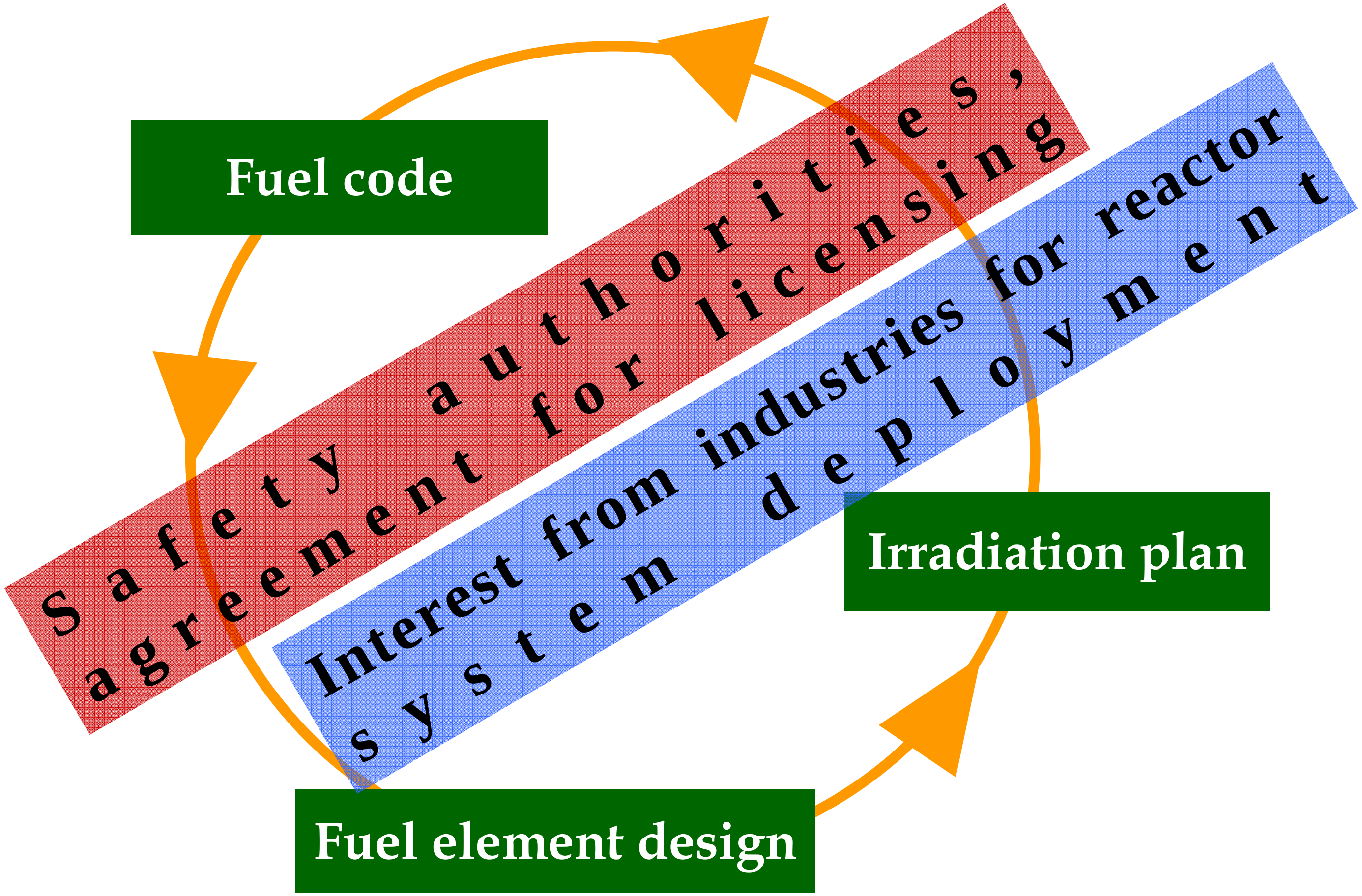
N. Chauvin, A. Courcelle, M. Pelletier, Y. Guerin,
JM. Escleine, M. Phelip, F. Michel, S. Bejaoui, M. Lainet

CEA-Cadarache, Fuel studies department


Fuel code
Irradiation plan
Fuel element design



Lower margin for fuel design → performances increase



Lower margin for fuel design → performances increase

Less uncertainties and higher confidence → safety enhancement

DEFINITIONS FOR EVALUATION

Fuel design phases, Irradiations types, Fuel code levels

→ Choice of examples

PART 1 : FUEL DESIGN AND QUALIFICATION WITH IRRADIATION PLAN

PART 2 : FUEL CODE AND VALIDATION WITH IRRADIATION

PART 3 : ILLUSTRATIONS OF IRRADIATION-FUEL DESIGN-MODELLING WITH GENIV FUEL EXAMPLES

CONCLUSION

Definition of fuel design

- **4 phases:**
  - Selection
    - Prospective approach to demonstrate feasability, to assess materials & design options
  - Development
    - Identify limitations and all items of interest for R&D
  - Optimisation
    - Improvement of safety and performances with : fabrication process, materials optimisation, design , ….
    - Normal and off-normal conditions
  - Qualification
    - Full size demonstration under prototypic conditions :
      neutronic + thermomechanic + thermohydraulic + thermodynamics
    - Licensing of fuel/core by regulator by identification of fuel limits

→ A quantitative and more detailed evaluation : Technical Readiness Level scale*

* *Global'09, K. A. McCarthy and K. O. Pasamehmetoglu, Paper 9477*

Definition of Irradiation types in reactor

NORMAL CONDITIONS

- **Analytical**
  - ***Objective*** → 1 phenomenon (creep, swelling, gas diffusion…..)
  - **Irradiation design:**
    - Geometry: conventional pellet or dedicated geometries (disk, samples, …),
    - Conditions: most are fixed to test 1 parameter
    - Monitoring and in-situ measurements
  - **Reactor :**

  → In MTR

  + in-pile measurements (pressure, FG release, fuel temperature, fuel stack elongation, fuel pin outer diameter change) with possibility to fix some conditions

  - thermal spectrum (or screen), different limit conditions except in dedicated loop,
  - miniature fuel rodlet, limited irradiation time

  → In prototype

  + representative conditions including fast neutron dose and high BU

  - no instrumentation, « Cook and look »

- **Integral or semi-integral**
  - ***Objective*** → phenomena coupling (Fission gas release, temperature, clad strain, …)
  - **Irradiation design**:
    - Pin or shorted pin with representative radial geometry
  - **Reactor** : *same*

NORMAL CONDITIONS

– **Analytical**

- ***Objective*** → 1 phenomenon (creep, swelling, gas diffusion…..)
- **Irradiation design:**
  - Geometry: conventional pellet or dedicated geometries (disk… amples, …),
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- **Reactor :**

→ In MTR

+ in-pile measurements (pre… , fuel stack elongation, fuel pin … ty to set some conditions
- thermal spect… …ons except in dedicated loop,
- miniature fuel …

→ In prototype

+ representative co… …s including fast neutron dose and high BU
- no instrumentation, « Cook and look »

Completed with out-of-pile separate effects studies

– **Integral or semi-integral**

- ***Objective*** → phenomena coupling (Fission gas release, temperature, clad strain, …)
- **Irradiation design**:
  - Pin or shorted pin with representative radial geometry
- **Reactor** : *same*

- **OFF-NORMAL CONDITIONS**
  - **Analytical**
    - MTR: overpower test on re-fabricated irradiated pin (slow transient)
    - Furnace heating test in hot lab: 1 pellet with/wo clad
      - annealing treatment or temp. ramp or even a local heating to have a temperature gradient on irradiated fuels above 2500℃ with different atmospheres (MERARG II – DURANCE devices in LECA hot cells facility at CEA-Cadarache)
      - on-line measurement of gas release : FG and volatile FP release.
  - **Integral or semi-integral** → phenomena coupling
    - Hot cells : severe accident conditions on irradiated rodlet (VERDON in LECA)
    - Safety reactor for fast transient test on a full size pin (CABRI, TREAT, …) or severe accident on pin bundle (*PHEBUS*).

Definition of code grade levels

- **LEVEL 1 ; Pre-design code**
  - Empirical models, simple ones and limited coupling
  - Check behaviour for pre-designing fuel

- **LEVEL 2 ; R & D code**
  - Dedicated models and material laws with models coupling
  - For fuel design & experimental irradiation design & post irradiation calculation

- **LEVEL 3 ; Fuel performance code**
  - 1.5 D (axi-symmetry), 2 D or 3D thermo-mechanical analysis,
  - Modelling increasingly mechanistic and multi-scale approach
  - Validation with large experimental database

- **LEVEL 4 ; Predictive code « THE HOLY GRAIL !! »**

  That can be used outside of its validation area with a high confidence on results :
    - Reliabiliaty (physics based models and model coupling)
    - Availability (application on a large area with spread irradiation database and material database)
    - Accuracy (high level for all situations)

  - Multiscale modelling (bubbles, grain, pellet, fuel element level) for whole fuel element evaluation as well as local effects (1.5D-2D-3D) and non symetric effects

    …. with microstructure and irradiation effects.
  - Coupling between thermochemistry, thermodynamic, transport theory, neutronic and thermal/mechanical conventional analysis

CHOICE OF EXAMPLES

- **GFR, plate and pin fuel with mixed carbide and refractory cladding (composite)**
  - Selection phase for fuel design
  - Fuel code development before irradiation programme
  - Irradiations for feasability studies on fabrication and behaviour

- **HTR, particle fuel**
  - Optimisation-qualification phase,
  - Fuel code development before the irradiation programme
  - Irradiations able to evaluate and improve both behaviour (models) and fuel fabrication : analytical and integral irradiations

- **SFR, driver MOX fuel**
  - Qualification phase
  - Fuel code existing, models improvement on-going
  - Irradiations to extend experimental database

- **SFR, transmutation homogeneous MOX fuels** $(U_{0.78}, Pu_{0.2}, Am_{0.013}, Np_{0.007}, Cm_{0.006})O_{2-x}$
  - Development phase
  - Fuel code existing, adaptation of some models
  - Irradiations to build dedicated database

- **SFR, MABB minor actinide bearing blanket** $(U_{0.8}, Am_{0.153}, Np_{0.034}, Cm_{0.013})O_{2-x}$ or $(U_{0.8}, Am_{0.2})O_{2-x}$
  - Selection-Development phase
  - Fuel code existing, need of dedicated models + adaptation of existing models
  - Irradiations to demonstrate limits and for model validation

Others possible applications : dispersion fuels for transmutation, metal fuel, ….

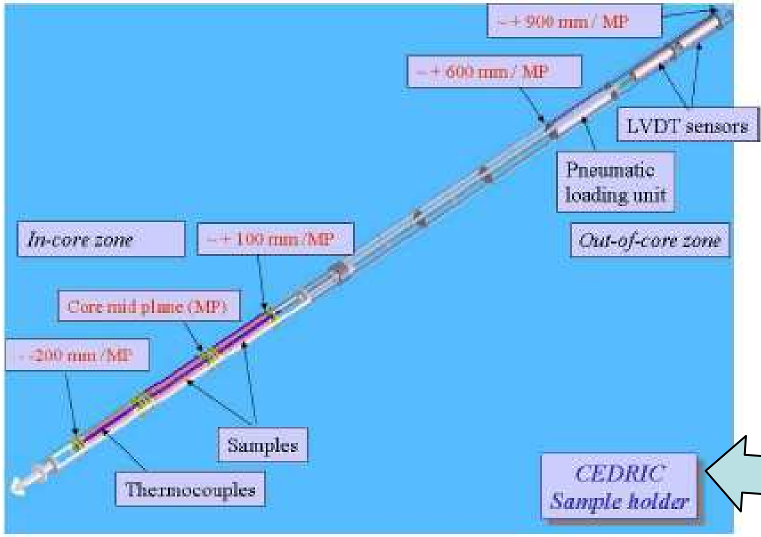
- **PART I : FUEL DESIGN AND QUALIFICATION WITH IRRADIATION PLAN**

SELECTION PHASE

- **Objective:**
  - Based on a first fuel design with several options (design/material)
  - → Evaluate performances towards requirements

- **Irradiation**
  - Screening irradiations in order to remove options due to critical points

- **Analytical**
  - GFR



Cladding:

- **FUTURIX-MI** (select the best cladding for high temp.-1000℃ and fast fluence-40 dpa), PHENIX, self-heating device with sample holder, different specimens, temperature evaluation by monitors.

- **CEDRIC** (SiC creep)
  OSIRIS, SiC fiber under constant stress (200MPa) and LVDT for on-line elongation measurement.

Concept :

- **FUTURIX-Concept** (select the best concept for GFR conditions, thermomechanical & thermochemical)
  PHENIX, pin-std rig with several fuel types (coated particles, honeycomb structure, nitride, carbide fuels,…).

DEVELOPMENT PHASE

- **Objective:**
  → Reference design
  → Specifications fulfill-Performances-limits-critical points

- **Irradiation**
  - Prototypic fuel (lab. scale fabrication)
  - Intermediate conditions (Burn Up and dose ↗ with a step by step approach)
  - Identification of normal conditions life limiting phenomena

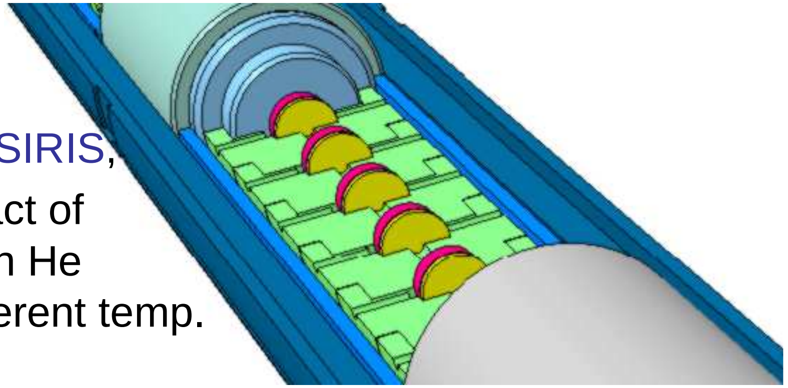
DEVELOPMENT PHASE : example

- **Analytical**
  - Homogeneous transmutation of Am
    - **AM1** in JOYO reactor for BOL phenomena
  - GFR
    - UPuC:
      - **GOCAR** (effect of temperature on MC swelling) SILOE reactor, special design with gap adjustment for temp. control, thermocouple
- **Integral**
  - Homogeneous transmutation of Am and Np
    - **SUPERFACT** (behaviour at intermediate burn-up)

    PHENIX, mean LHR, 7at%
  - GFR
    - UPuC:
      - **NILOC,** HFR
      - **NIMPHE**, PHENIX
      - **L414**, JOYO
      - **AC3**, FFTF
      - **Transient tests in** TREAT….
    - *Plate and pin prototype first test*

DEVELOPMENT PHASE : example

- **Analytical**
  - MABB
    - **MARIOS & DIAMINO** in HFR & OSIRIS,
    - Screening experiment on the impact of MABB fabricated microstructure on He behaviour under irradiation at different temp.



- Exp. Device: self-heating device (TZM), fuel disk
- Temperature controlled with gas composition and constant in the disk with axial thermal exchanges to avoid thermal gradients
- Radial and axial gaps to let free swelling of discs.

- Conditions and parameters:
  - 4 temp. : 600-800-1000-1200℃
  - 2 microstructures
  - 2 He production rates
- Irradiation : 2010 (MARIOS) 2011 (DIAMINO).

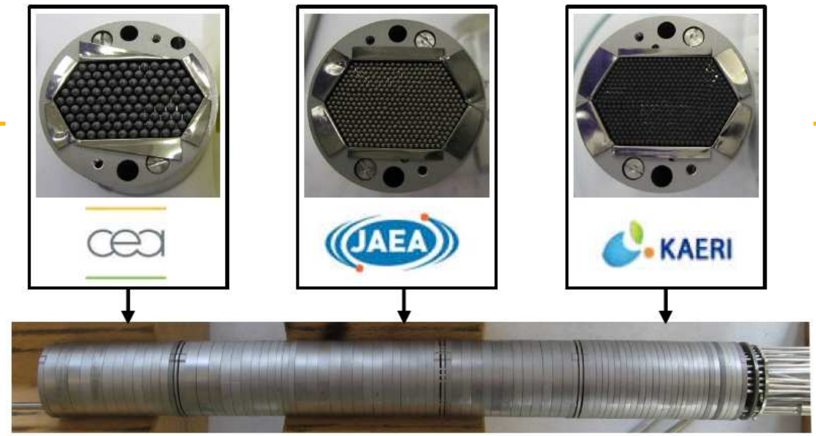
OPTIMISATION PHASE

- **Objective:**
  - → Performance improvement
    - → Reliability
    - → Safety
    - → Cost
    - → Limits

- **Irradiation**
  - – Representative conditions: in FR or in dedicated loop system in MTR
  - – Representative fuel element with industrial fabrication

OPTIMISATION PHASE : example

- **Analytical**
  - HTR
    - **PYCASSO in** HFR



Objectives (CEA):

- PyC densification kinetics (tangential and radial strain) under neutron fluence
- Comparing geometrical changes with ATLAS numerical calculations

Design

- Several conditions: free of stress or representative stress on PyC
- Two stacks of 14 disks are irradiated, at 900 & 1100℃ , with maximum fast neutron fluence 2 x 10^{25} m^{-2}
- Temperature monitoring with gas composition adjustment + TC on device structure
- Avril. 2008 – Avril 2009

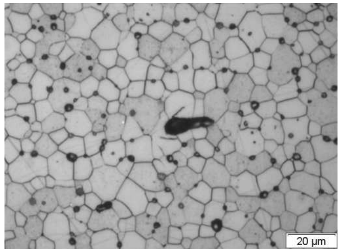
Schematic representation of the CEA specimens for PYCASSO-I.

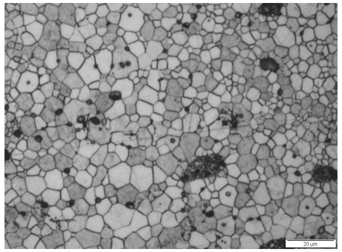
	kernel/buffer	kernel/buffer/PyC	kernel/buffer/SiC	kernel/buffer/SiC/PyC
Ø/épaisseurs [µm] échelles schémas : x 10 et taille réelle sous format A4	1000/250	1000/250/40	1000/215/35	1000/215/35/40

CADARACHE

OPTIMISATION PHASE : example

- **Analytical**
  - Homogeneous transmutation
    - **AF-2C, 2D**, ATR
      - FCCI at high Burn Up
- **Integral**
  - SFR : coprecipitated MOX
    - **COPIX**
      - Objective : compare fuel irradiation behaviors between Co-precipitated UPuO2 and French reference fabricated by COCA process. PHENIX.
      - 2 O/M (**1,937 and 1,965**),
      - 2 pins with 2 fabrication routes (direct or dilution) → 2 microstructures
      - Sept. 2008 – March 2009 **, 4-5 at% - 420W/cm**



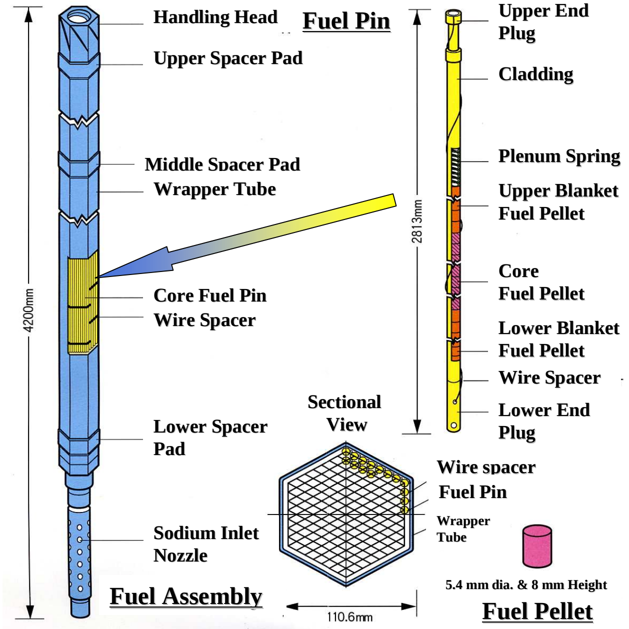


  - Homogeneous transmutation
    - **GACID step1&2**
      - Objective : demonstration that MOX driver fuel can transmute MA's (Np/Am/Cm) with reduced impact on fuel behaviour. JOYO & MONJU
      - ***Design & fabrication process in progress***

GACID

STEP1 :$(U,Pu_{0,25},{}^{241}Am_{0,03},Np_{0,01})O_x$

STEP2: $(U,Pu_{0,25},{}^{241}Am_{0,03},Np_{0,01},Cm_{0,002})O_x$



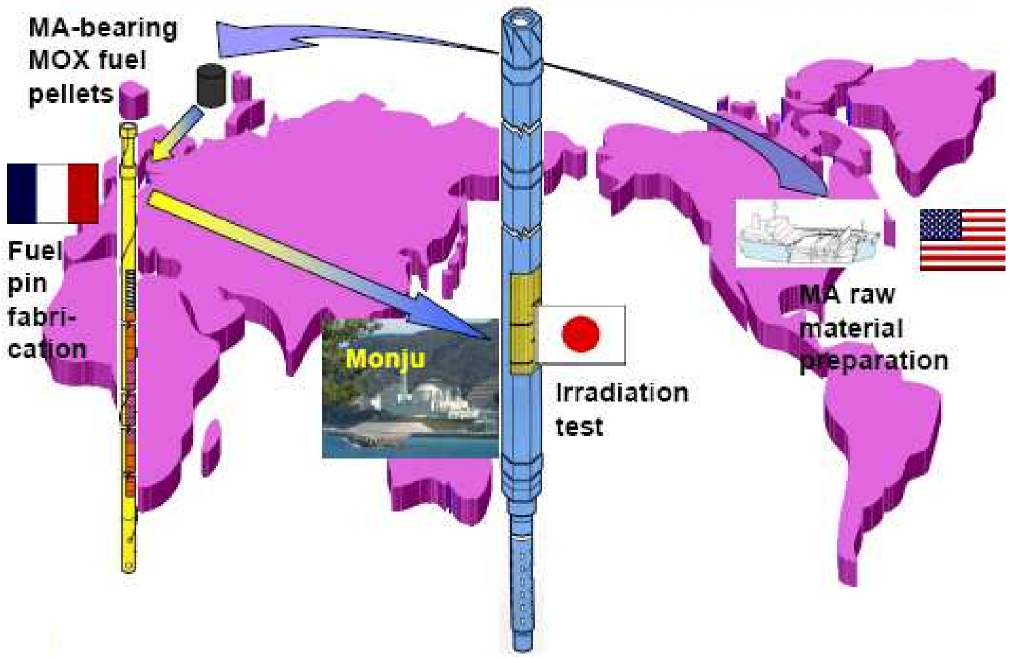
QUALIFICATION PHASE

- **Objective:**
  - Demonstration of performance and reliability in normal and off-normal conditions at full sub-assembly scale
  - Directly useful for industrial applications : fuel cycle (specification fulfill) and reactor prototype (safety licensing).

- **Irradiation**
  - Full sub-assembly scale
  - Fabrication in an industrial plant with pilot processes
  - Representatives conditions for sub-assembly in a prototypic reactor

QUALIFICATION PHASE : example

- **Integral**
  - Homogeneous transmutation
    - **GACID step 3**
      - Bundle-scale MA-bearing Fuel Irradiation Demonstration in MONJU



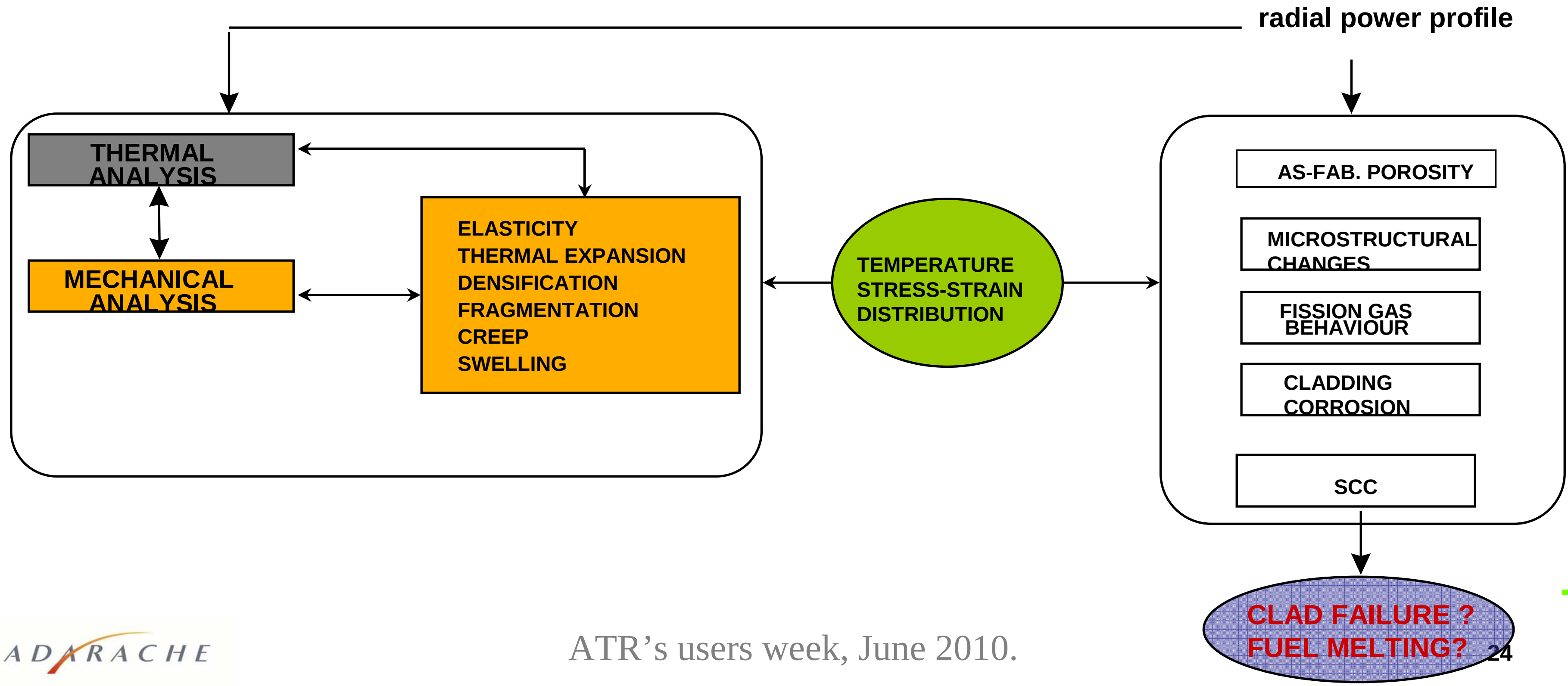
- **PART II : MODELLING AND EXPERIMENTAL VALIDATION**

Fuel Modelling : principles

- **In pile behaviour:** several phenomena
  - Complex
  - Simultaneous
  - Coupled

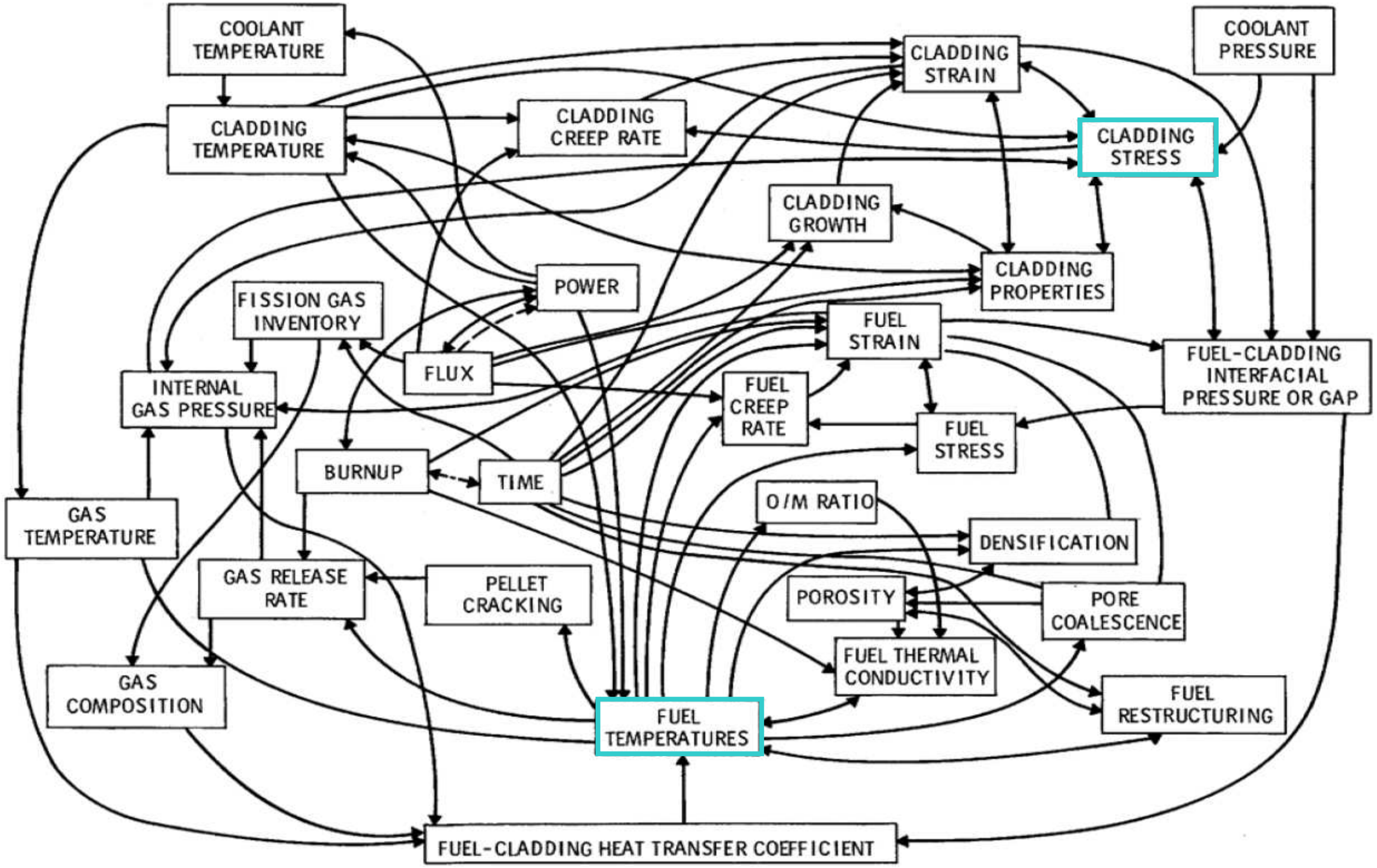
  …and with irradiation induced changes in materials

- **Schematic view of how models interact**



Fuel Modelling : real life

- **Complete view of how models interact !!!**

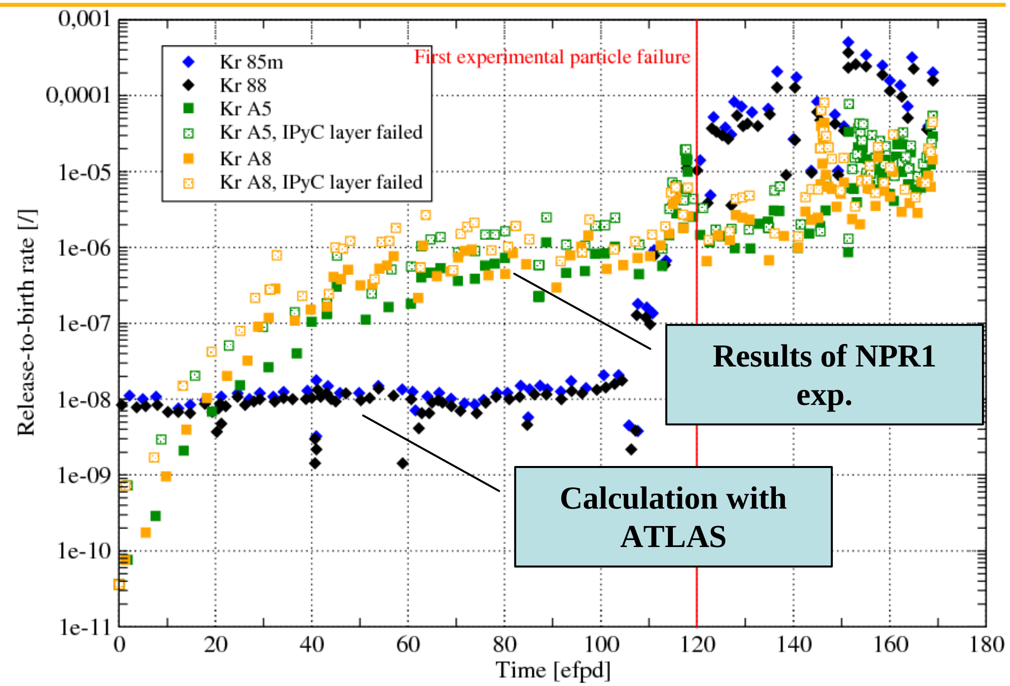


- **Ref. Manning et al., MMSNF conference**

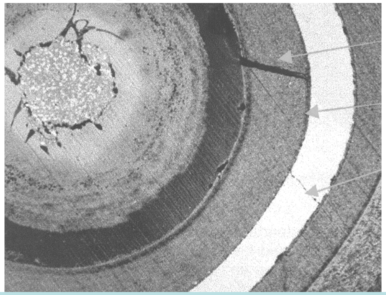
HTR fuel : PyC densification

- **Current model**
  - PyC is orthotropic and anisotropy evolves with conditions
  - Stresses are relaxed in PyC by irradiation induced creep.
  - Too high stresses could lead to PyC and SiC cracks.

- **Results : C/E**
  - No direct measurement, only particle failure rate (Xe & Kr release to birth)
  - Calc. surestimates particle failure

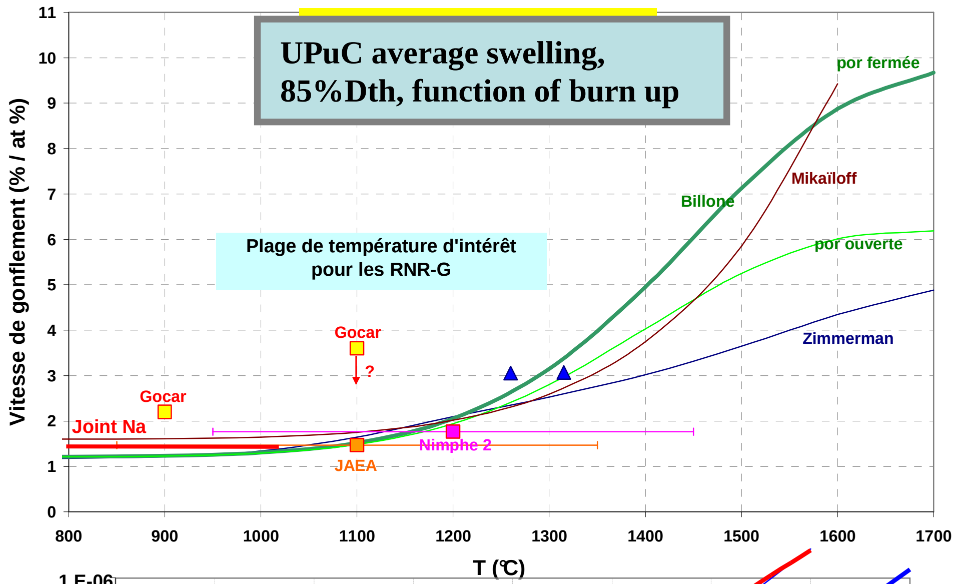


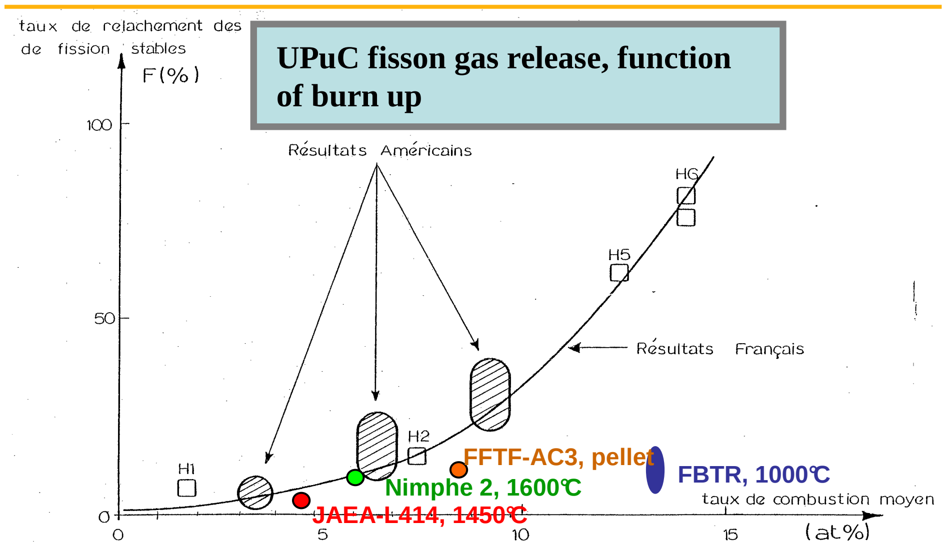
Particle failure initiated by PyC crack

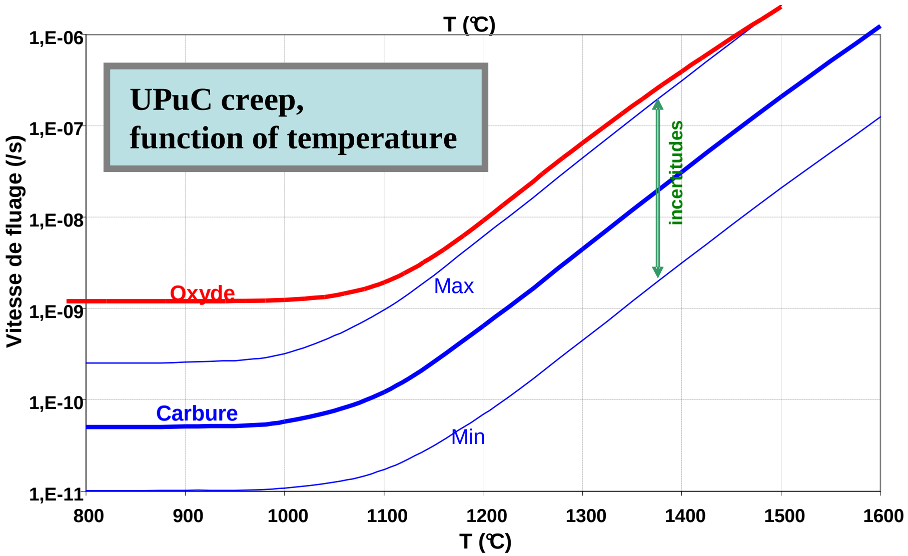


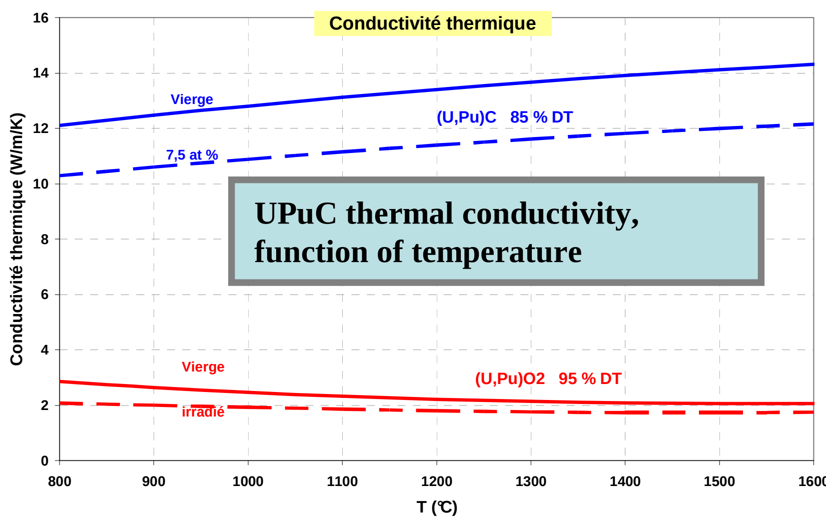
→Current C/E discrepancies have significant impact on :
Particle failure evaluation (SiC Weibull approach) → first HTR fuel criteria (direct cycle)

GFR fuel : UPuC models



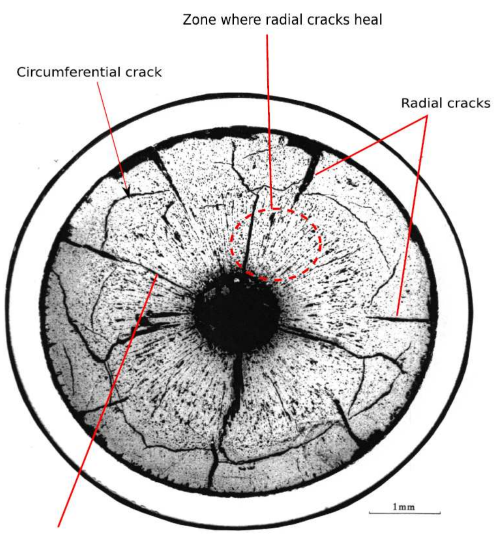






→ UPuC behaviour very complex with high level of uncertainties

SFR MOX fuel : microstructure evolution

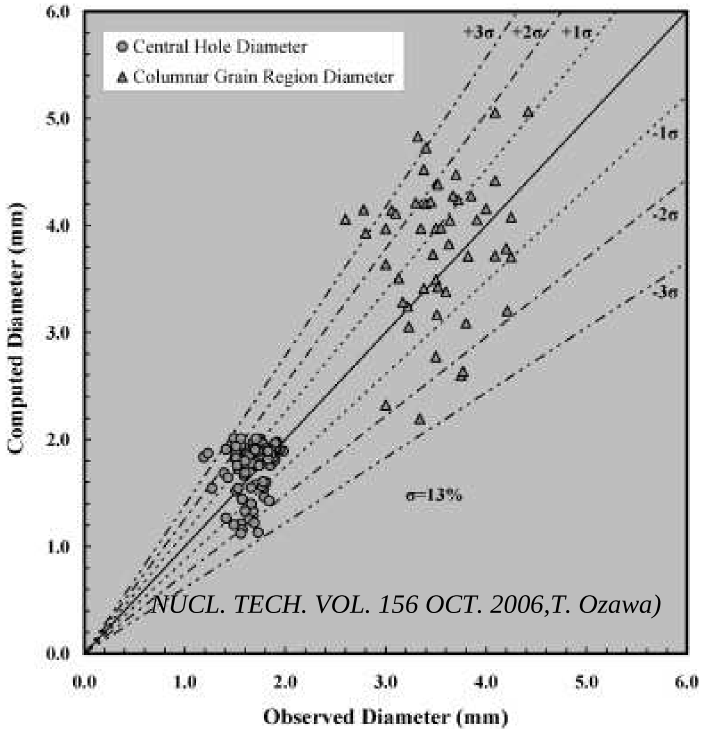


Current Models

Different conditions , space and time dependent : temp. and temp. gradient, LHR evolution, local composition, evolution (O, actinides)

- Gas and solid swelling
- Porosity movement
- Coalescence model (central hole)
- Crack location

- **Results: E/C**
  - Exp. parameters : central hole, columnar grain diameter, clad strain, porosity field,
  - Calc. predict central hole and columnar grain at ±25%



→**Current C/E discrepancies have significant impact on:**

Margin to melt

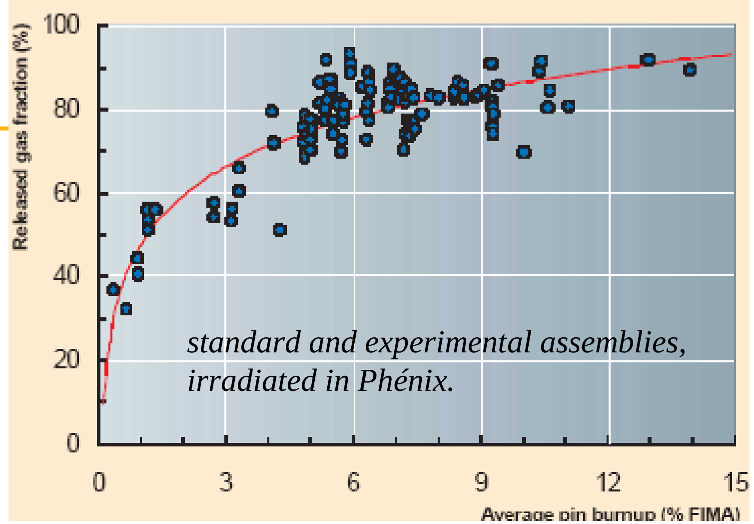
Max BU depends on central hole closure to avoid severe FCMI.

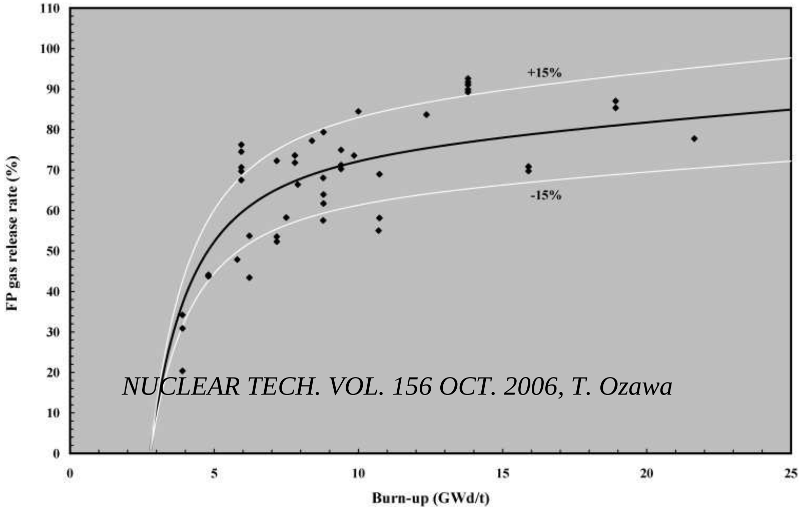
SFR MOX fuel : Fission gas release

- **Current model**
  depending on almost all the others models (JOG, FCCI, swelling, clad creep, restructuration, diffusion…)

  3 types of model:
  – Simple correlation with temp., BU
  – Grain size (Booth-like model)
  – Full model including known mechanisms (defect, intra-extra grain diffusion, cavities type, bubbles ….)

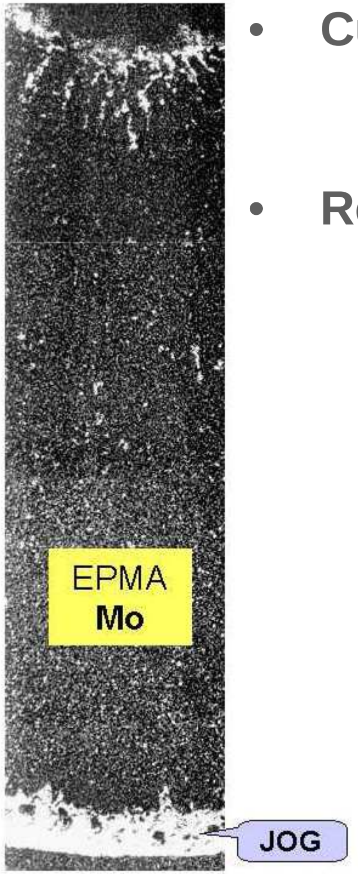
- **Results : C/E**
  – Exp. parameters : FGR measurement or in-situ pressure and FP analysis + fuel retained gas distribution
  – Calc. predict FGR at $\pm$15%





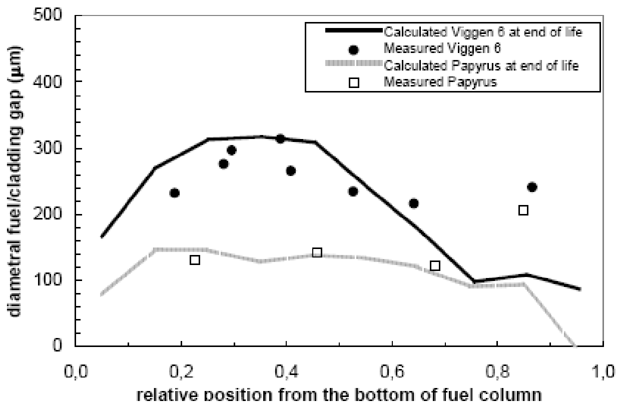
→ **Current C/E discrepancies have significant impact on :**
Strong impact on temperature
As inner pressure is a clad limiting point, conservative approach

SFR MOX fuel : Pellet to clad join (JOG)

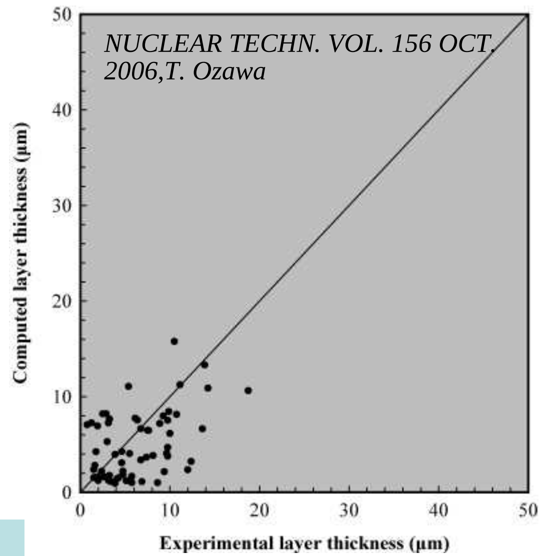


- **Current model**
  - Cs production → Chemical state prediction (Cs_2MoO_4) → radial (pellet) and axial (gap) transport
- **Results : C/E**
  - Exp. parameter : JOG thickness, retained Cs
  - Cal. underestimate JOG thickness at TOP and even at PPN

  →high uncertainties on transport mechanism, axial extrusion, temperature



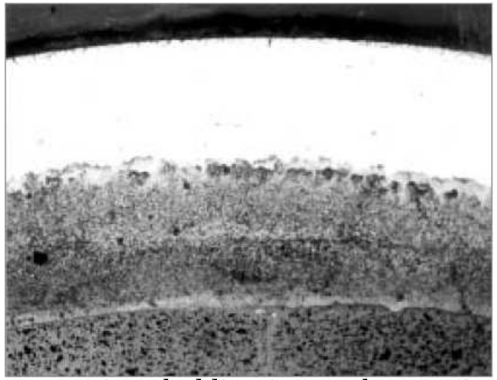
Comparison cal/meas for axial evolution of fuel clad gap with GERMINAL Code



→Current C/E discrepancies have significant impact on :

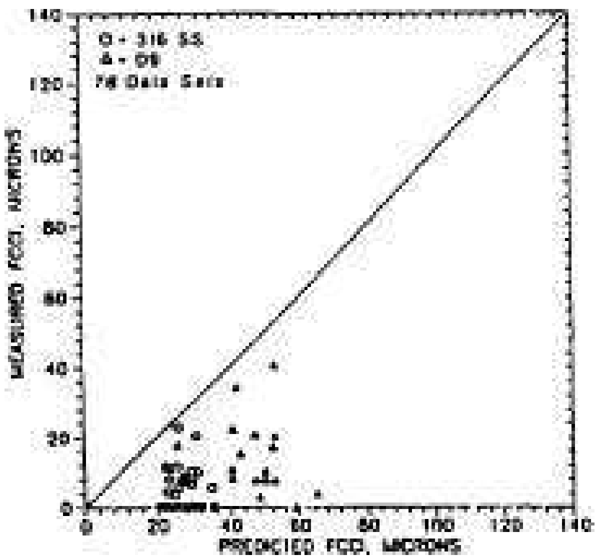
temperature and clad strain (max. burn up)

SFR MOX fuel : FCCI



Extensive cladding internal corrosion (~ 40% initial thickness), in an experimental Phénix fuel element, 15–15 Tiε steel, 16.9at%, 155 dpa.

- **Current Models**
  good understanding of mechanism but full model (neutronic-thermodynamic-transport-thermodynamic) is still missing
  - Simple correlation with BU, temperature



measured maximum FCCI depths in FFTF with predicted value (IAEA, TECDOC-1083)

- **Results: E/C**
  - Exp. parameters : axial internal corrosion depth
  - Calc. surestimates FCCI in all cases

→ Current C/E discrepancies have significant impact on :

Clad failure risk evaluation

SFR MOX fuel : Thermal behaviour

- **Challenge :**
  reduce uncertainties to increase temperature (B.U./LHR) with a reliable approach

- **Objective : accurate prediction of temperatures (+/- 50-100°C) everywhere in fuel pin & in any situation.**

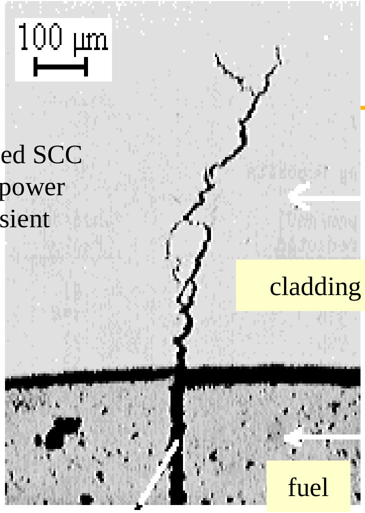
- **Open questions :**
  - **Heat transfer in the gap before full gap closure with JOG?**
  - **Heat transfer at high burnup (JOG conductivity)?**
  - **JOG axial transfert, impact on temperature at top of FC?**
  - **Thermal conductivity λ of fuel at high burn-up (large degradation? effect of species redistribution?)**

→In reactor measurement of centre-line temperature

Approach currently chosen to validate our thermal calculation

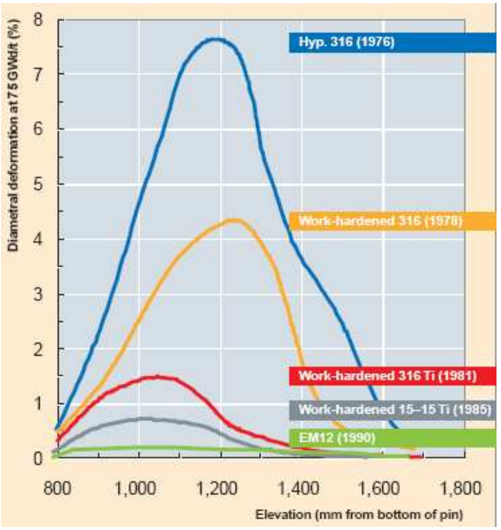
Need to be associated with others measurements to fix the others parameters (FGR, diameter change,…)

SFR MOX fuel : Mechanical behaviour



- **Challenge :**
  - reduce uncertainties to increase burnup/LHR
  - improve knowledge to propose enhancement (microstructure or dopant) like PWR

- **Objectives**
  - Predict all dimensional changes: clad strain (5-10% of max. strain), gap closure
  - Predict the risk of clad failure during power increase



- **Open questions**
  - Fuel : swelling, creep, cracking coupling ?
  - Clad: Creep, swelling at high burn-up/temperature (ODS)?
  - FCCI : high accuracy for all clad and all fuel compositions and conditions (model based on FP diffusion, oxide compounds thermodynamic). How clad properties affected by FCCI?
  - FCMI: max burn up for normal conditions and threshold of over-power or over-temperature during transient ?
  - what happen with MC/ODS, dispersed fuel/SS, MC/SiCSiC$_f$ (balance fuel creep-swelling and clad creep-swelling)?

→ Mechanical properties of fresh and irradiated fuel and cladding
→ In reactor : clad strain measurement and ramp tests in MTR

Modelling challenges

- **GFR fuel**
  - MC creep, swelling, FGR comprehensive models
  - SiC-SiC$_f$ yield and fracture strength, swelling vs temperature, fluence
  - MC-SiCSiC$_f$ coupling: clad stress and max strain at high doses

- **HTR**
  - Models validation with experimental results (characterisation based)

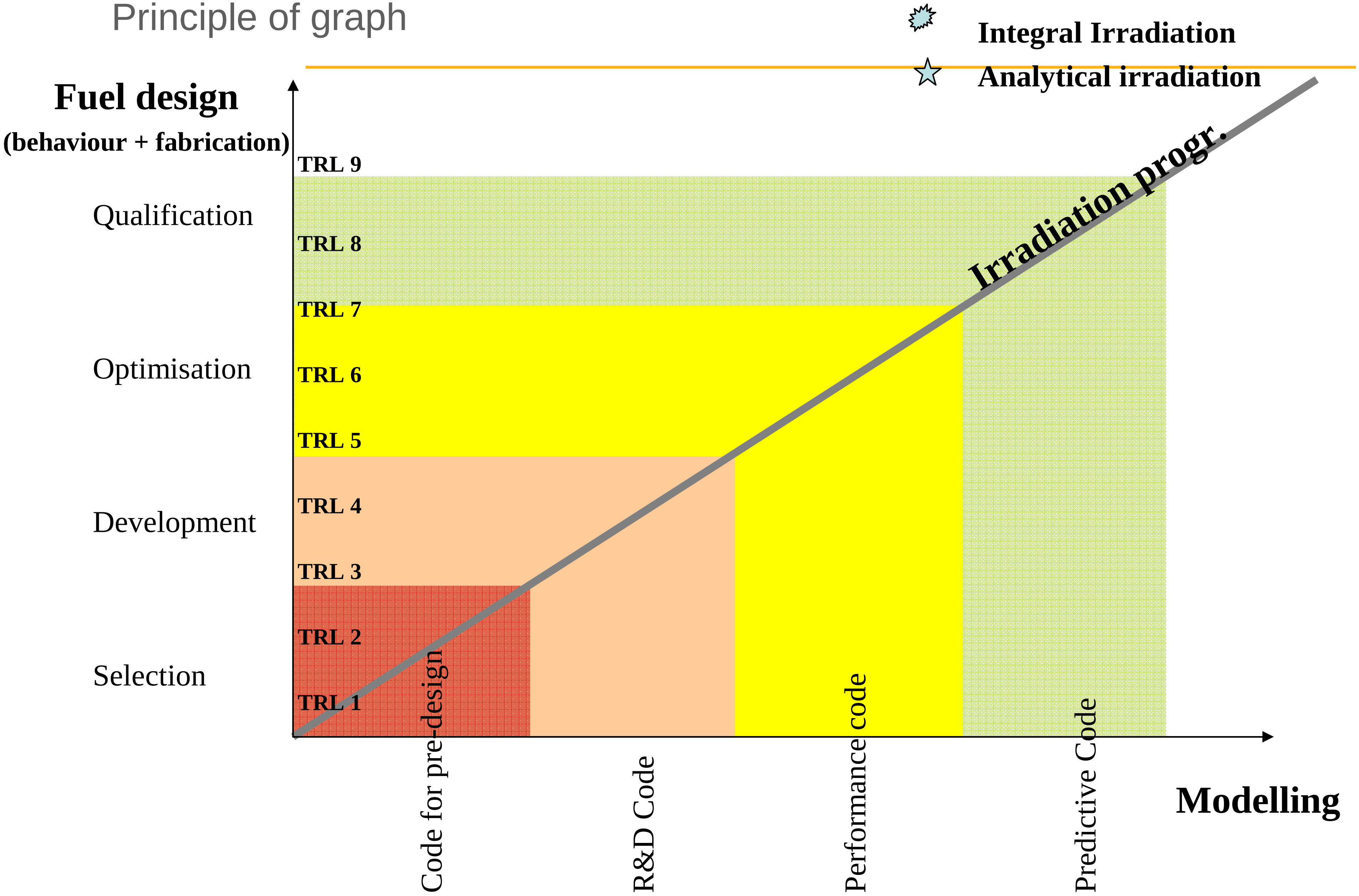
- **SFR MOX driver fuel**
  - Pellet behaviour at high BU and effect on clad stress
  - Burn up linked phenomena: FCCI (clad wastage), JOG
  - During transient: thermomechanical behaviour at high burn up
  - Species diffusion coupled with thermodynamic

- **MOX Homogeneous fuel**
  - Impact of MA on FCCI, FCMI at high burn up (thermodynamic) and margin to melt to be checked

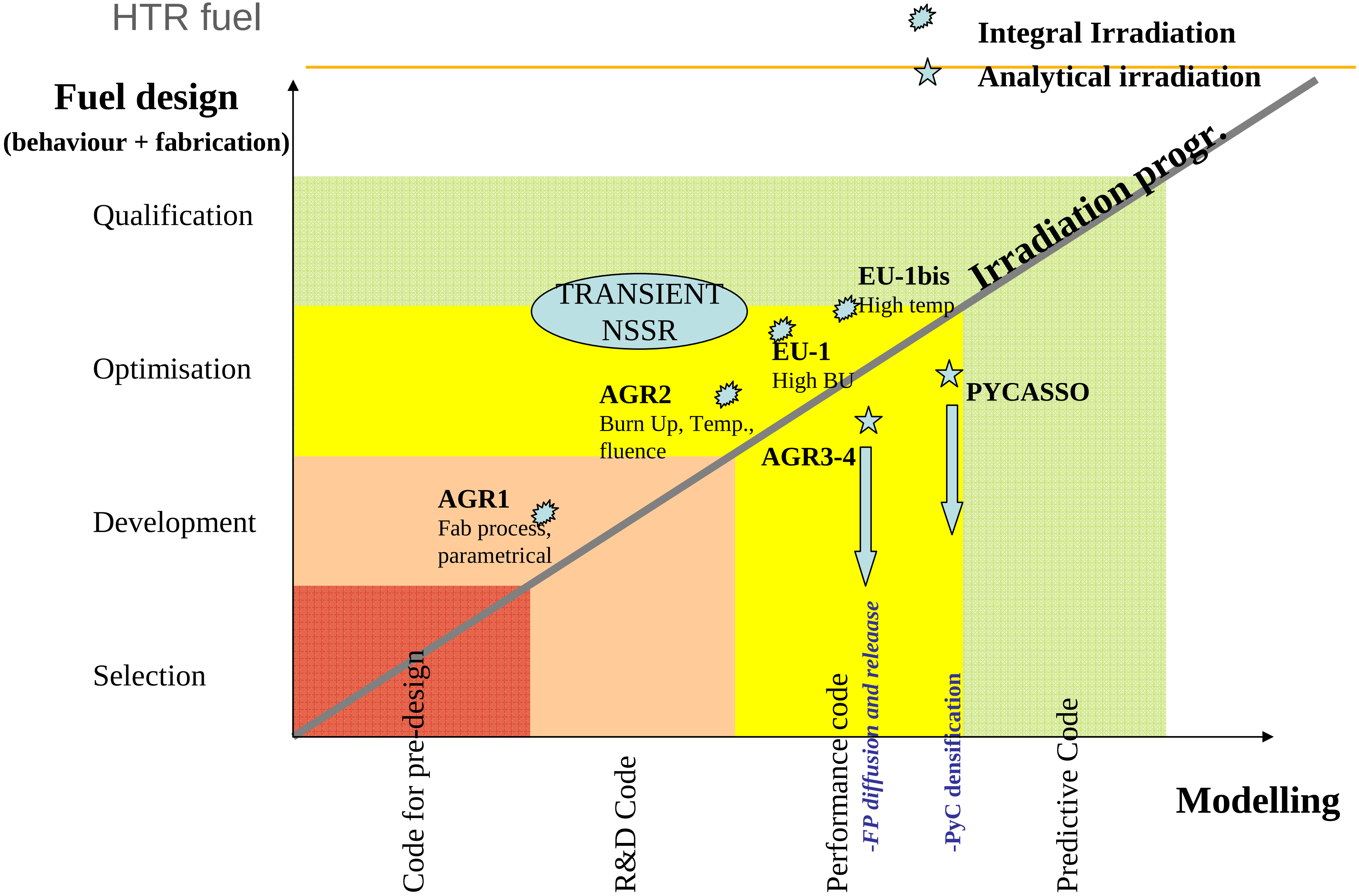
- **MABB**
  - Development of models based on UO_2 behaviour, completed with Helium production and release. Need to take microstructure (homogeneous/heterogeneous) into account.

- **PART III : ILLUSTRATIONS OF IRRADIATION-FUEL DESIGN-MODELLING WITH GENIV FUEL EXAMPLES**

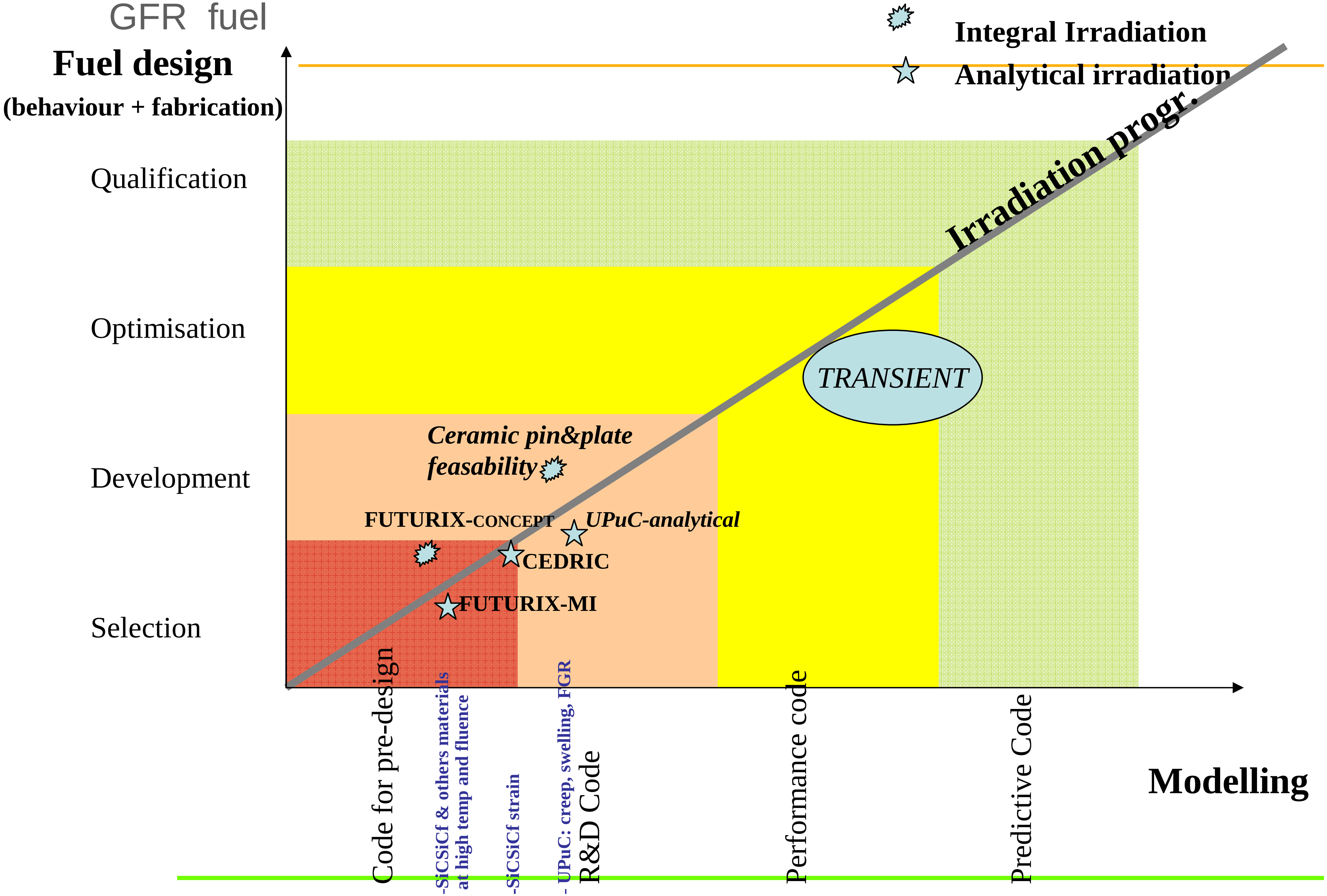
Principle of graph



HTR fuel

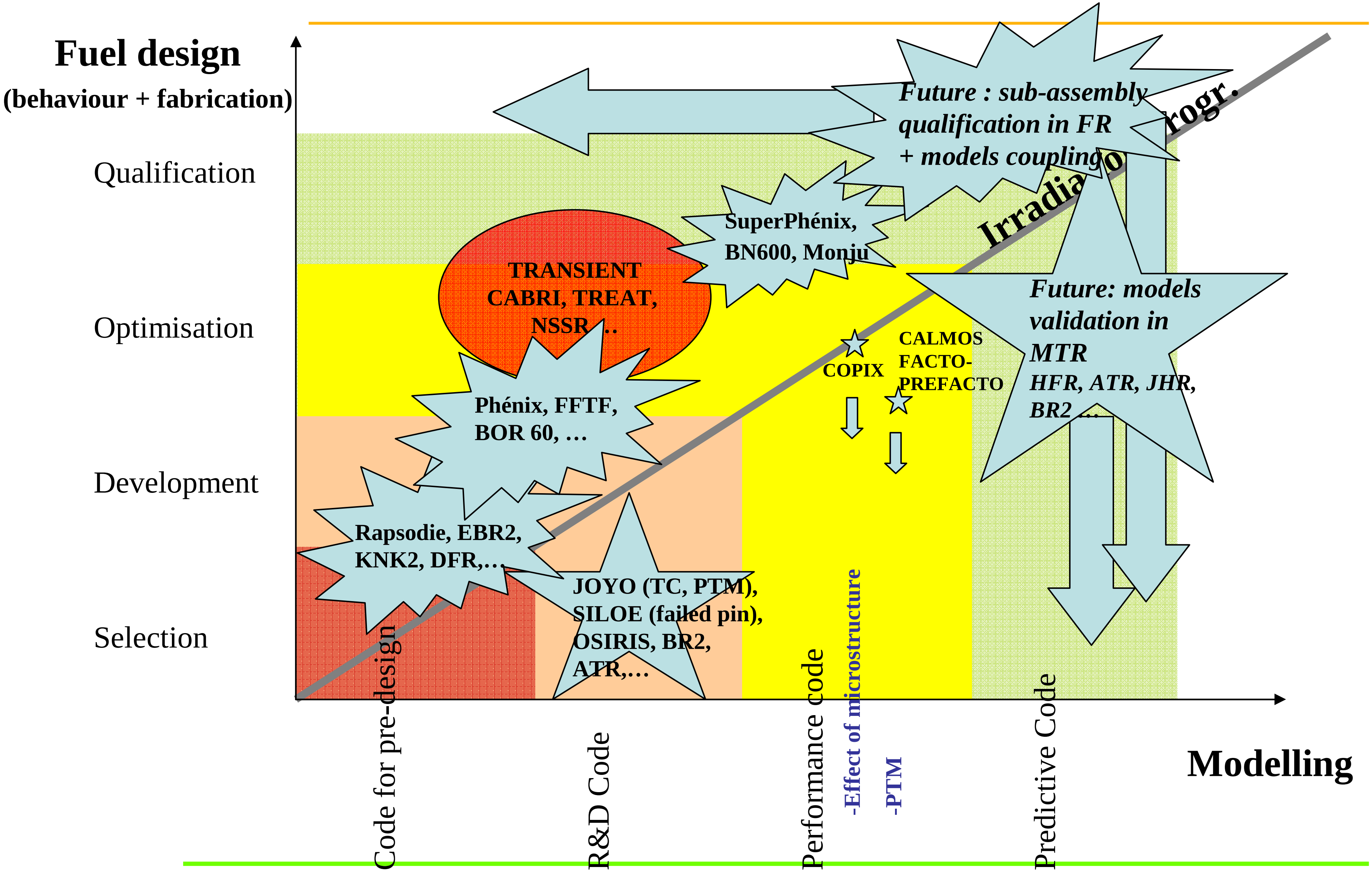

Integral Irradiation
Analytical irradiation
Fuel design
(behaviour + fabrication)
Qualification
Optimisation
Development
Selection
Irradiation progr.
TRANSIENT NSSR
EU-1bis
High temp
EU-1
High BU
AGR2
Burn Up, Temp., fluence
PYCASSO
AGR3-4
AGR1
Fab process, parametrical
-FP diffusion and releaase
-PyC densification
Code for pre-design
R&D Code
Performance code
Predictive Code
Modelling

GFR fuel

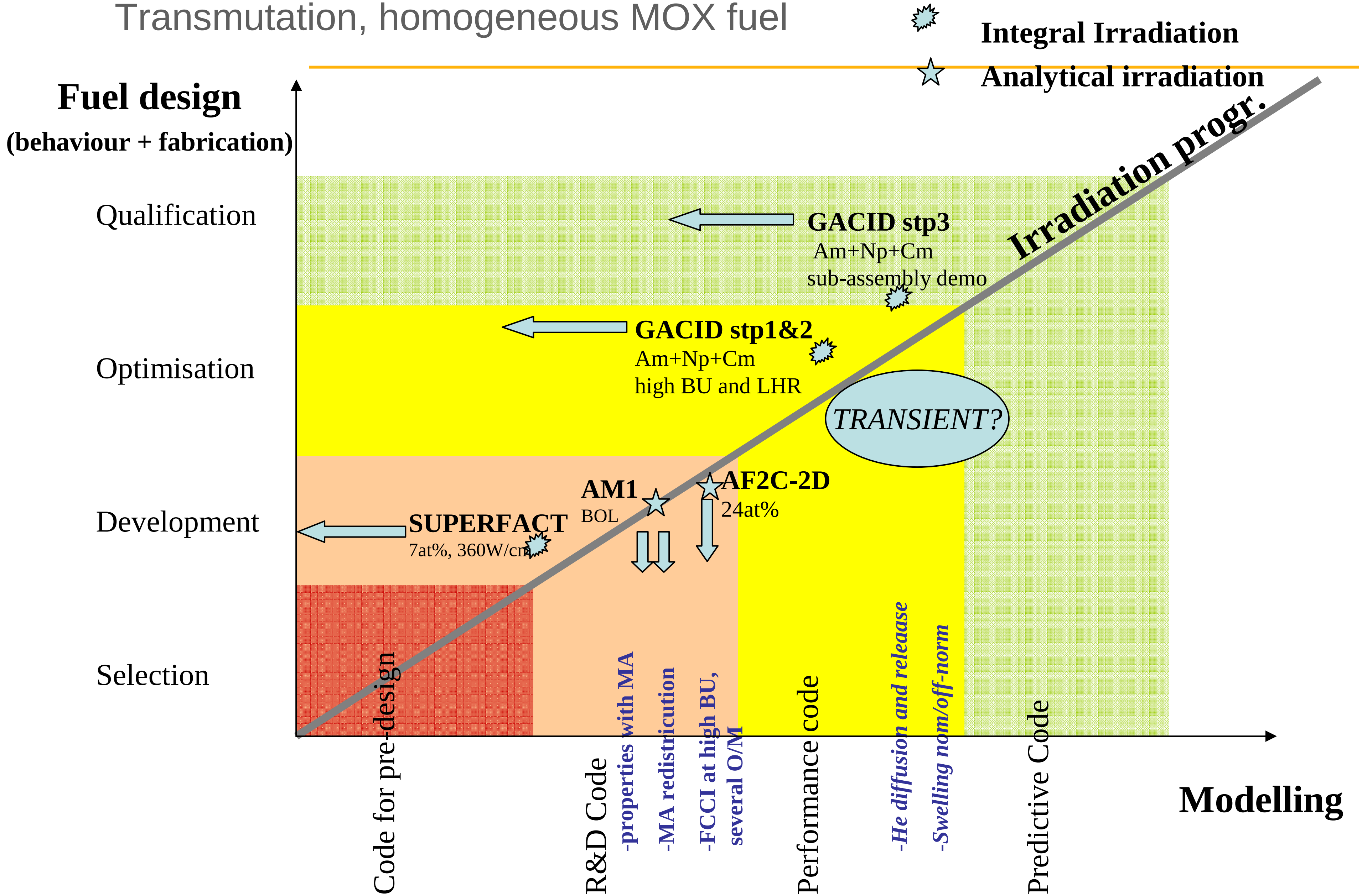


Integral Irradiation
Analytical irradiation
Fuel design
(behaviour + fabrication)
Qualification
Optimisation
Development
Selection
Irradiation progr.
TRANSIENT
Ceramic pin&plate feasability
FUTURIX-CONCEPT
UPuC-analytical
CEDRIC
FUTURIX-MI
Code for pre-design
-SiCSiCf & others materials at high temp and fluence
-SiCSiCf strain
- UPuC: creep, swelling, FGR
R&D Code
Performance code
Predictive Code
Modelling

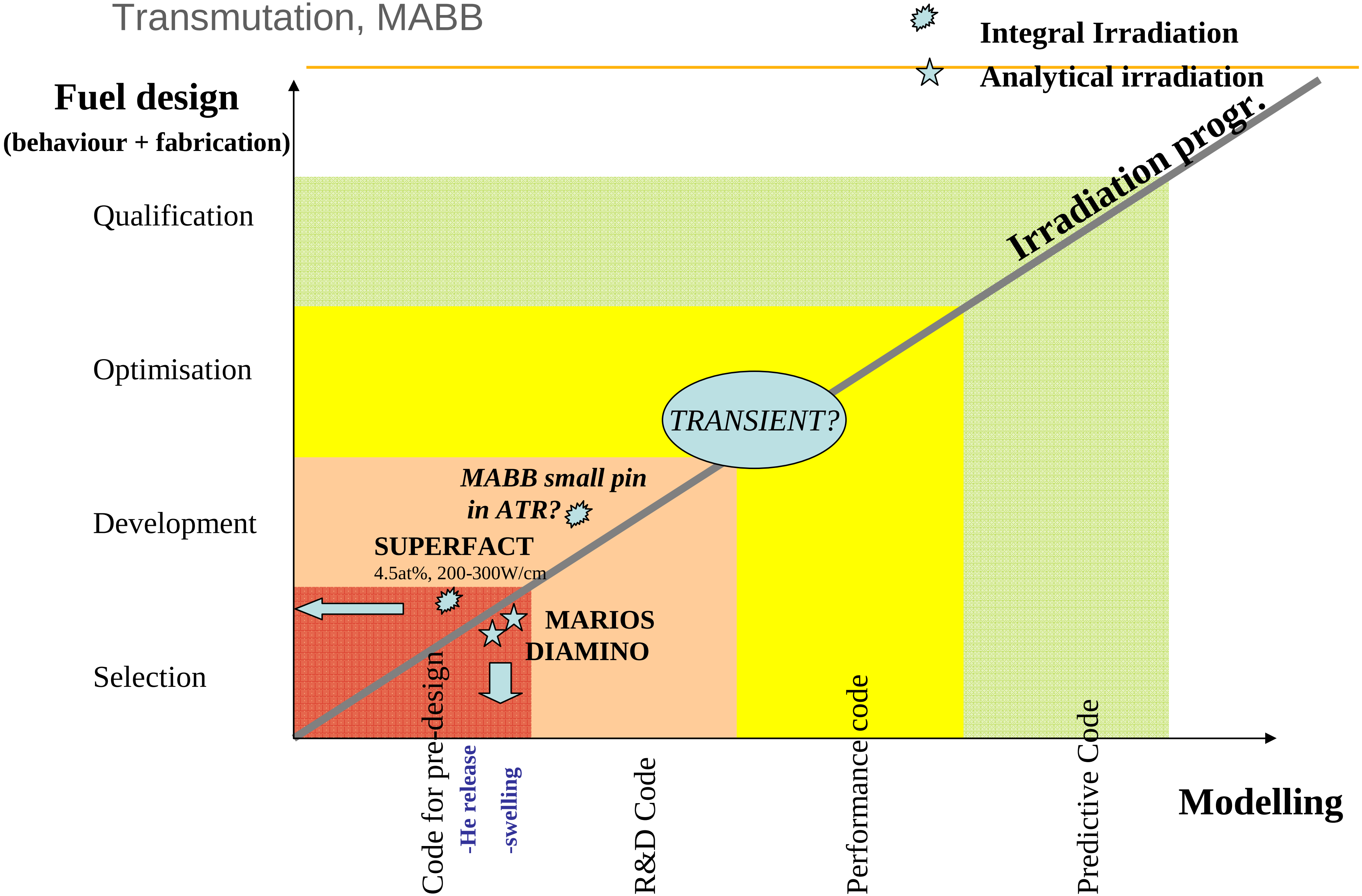
SFR- MOX driver fuel



Transmutation, homogeneous MOX fuel



Transmutation, MABB



Classical link between fuel design-irradiation-code

Irradiation gives results for code qualification

Fuel design → irradiation design → Irradiation results →Models devt. and code validation

Since 2000….

- → Because there is less and less MTRs and SFRs where it's possible to make experiments
- → Because of cost :
  impossible to have several hundreds points for 1 configuration
- → Because modelling has undertaken major steps (numerical methods, computer capacity, fuel behaviour knowledge, …)

Models validation gives specification for irradiations

Fuel design → calculation → models requirements→ irradiation design → Irradiation results

Nevertheless,

- ***Less than <u>20 parameters</u> may be checked with PIE results***
- ***Less than <u>5 parameters</u> may be measured in pile***
- ***Part of calculation uncertainties are due to data evaluation (fabrication- properties-irradiation conditions)***

Improvement on modelling MUST BE COMPLETED with

→*More accuracy on fabrication data and irradiation conditions*

→*More instrumentation in core, especially in MTR (also in prototype?)*

→*More characterisations in hot cell.*

THANK YOU FOR YOUR ATTENTION
THANK YOU FOR INVITING ME HERE